Micromagnetic Modeling of Static and Dynamic Properties of Ferromagnetic/Antiferromagnetic Bilayer

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***Abstract* — Static and dynamic properties of ferromagnetic (F) antiferromagnetic (AF) bilayer have been studied by using micromagnetic calculations. The reasonable value of exchange bias field has been obtained. In addition, we have shown the strong dependence of a resonance frequency F/AF structure on an angle between an external magnetic field and an easy axis of the bilayer.**

***Index Terms* — absorption spectrum, exchange bias, micromagnetic modeling.**

I. Introduction

THE phenomena of the exchange bias was discovered more than 50 years ago by Meiklejohn and Bean [1], who found that fine particles of partially oxidized Co exhibit magnetization curves with an unusual displacement along the field axes, as though there were a "bias" field (H_{eb}) in additional to the applied field. Experiments by Bean [2] on Co/Co-O thin films demonstrated that the exchange bias is preliminary an interface phenomenon and originate from the exchange interaction between ferromagnetic and antiferromagnetic layers.

In recent years exchange bias in thin films has found important technological applications in such devices as magnetoresistive sensors [3]. Moreover, F/AF bilayer structures are the perspective materials for high-frequency devices because the exchange bias field changes the ferromagnetic resonance frequency (FMR) significantly [4].

However, the fundamental origin of exchange bias phenomenon is still unclear [5], [6]. The Meiklejohn and Bean (M&B) model [1] predicts the value of the bias field much larger than those observed and fails to explain enhancing of the coercitivity. Furthermore, it was found that the exchange bias appears in F/AF systems with various configurations of magnetic moments. Therefore, those models which give more realistic value of H_{eb} [7]-[9] have to be limited to only certain arrangement of magnetic moments in the antiferromagnetic layer.

In this work we present static and dynamic studies of the ferromagnetic/antiferromagnetic bilayer by using a micromagnetic calculation. We assume that the F/AF interface occurs at an ideal uncompensated (all magnetic moments aligned) plane of the antiferromagnet.

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II. Details of Micromagnetic Modeling

We use full micromagnetic numerical calculations, which include all general magnetic interactions in a sample. The studies were carried out with a program "MultiLayers 2" which we have created. This program provides a numerical analysis of magnetic object properties based on the micromagnetic simulation. The heart of the calculation is proposed by the authors method of modeling of magnetic medium via a generalized interactions matrix. This method presents a way to investigate static and dynamic properties of magnetic structures with high detailing [10], [11].

We study a simple model of the ferromagnetic/antiferromagnetic bilayer, with 28 monolayers of AF and 12 monolayers of F. We assume that all magnetic moments in each monolayer rotate coherently, whereas between monolayers they may deviate significantly. Fig.1 shows schematic presentation of the model.

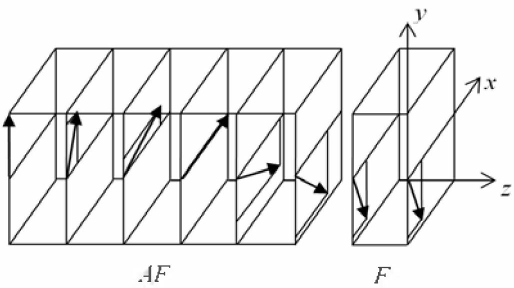

Fig. 1. Sketch of the F/AF model. For the AF layer magnetic moments only one sublattice are shown.

The distance between monolayers is consistent with the average lattice constant $a = 3.5$ Å. The following parameters for the AF layer were put into the simulation: the exchange constant $A_{AF} = -1\times10^{-8}$ erg/cm, the saturation magnetization $M_{AF} = 200$ G, the uniaxial magnetic anisotropy $H_{a(AF)} = 1$ kOe,

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which corresponds to the representative parameters of FeMn. The characteristics of the ferromagnetic layer are typical for the polycrystalline permalloy (Ni_{80}-Fe_{20}): $M_F = 800$ G, $A_F = 1\times10^{-6}$ erg/cm, $H_{a(F)} = 25$ Oe. A ferromagnetic alignment of magnetic moments across the interface is assumed and the exchange constant is $A_{AF\text{-}F} = 1\times10^{-9}$ erg/cm. Thicknesses of AF and F layers are $t_{AF} = 98$ Å and $t_F = 42$ Å, respectively. In present modeling we do not account for the influence of the temperature.

III. Results and Discussion

A. Static properties

Fig. 2 shows calculated hysteresis loops of the F/AF bilayer for two cases: an external magnetic field H was applied along an easy axis and along a hard axis of the antiferromagnetic. One can see that in the former case the result of the exchange interaction between AF and F layers is bias of the hysteresis loop along the field axis with magnitude $H_{eb} = 124$ Oe. At the same time, when the external field was applied along the hard axis, the exchange bias field was near to zero. The calculated value of H_{eb} is in good agreement with experimental data obtained in [12] for the similar structure. For the FeMn (89 Å) / Ni-Fe (40 Å) bilayer the measured bias field was 125 Oe.

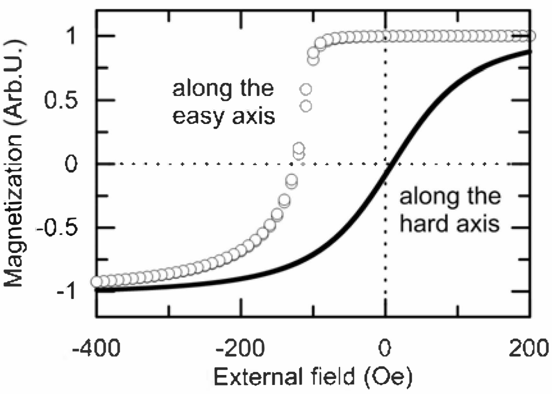

Fig. 2. Calculated hysteresis loops of the F/AF structure for two directions of the external magnetic field.

In addition, we compared the findings of the micromagnetic simulation with theoretical data of some common models. According to M&B model, the expression of the exchange bias field can be written as follows [3]: $H_{eb} = J_{eb}/M_F t_F$, where $J_{eb} = 2A_{AF\text{-}F}/a$. Substituting parameters from Section II one can obtain $H_{eb} = 170$ Oe, which somewhat larger than our results. The main reason of such difference is that in M&B model for the F and AF layers the single domain approximation is used. However, the analysis of micromagnetic modeling outcomes shows that during the magnetization reversal process the AF magnetic moments are gradual turning parallel to the interface (see Fig. 1). Apparently, this leads to reducing of the influence of the antiferromagnetic layer on the ferromagnetic one and decrease of H_{eb} value.

The magnetization configuration obtained from our simulation is in qualitative agreement with a domain wall model proposed in [9], where Mauri *et al.* suggested that in an antiferromagnetic layer the domain wall (parallel to an interface) formed. They found the following expression for the exchange bias field

$$H_{eb} = \frac{J_{eb}}{M_F t_F}\frac{2\sqrt{A_{AF}K_{AF}}}{\sqrt{J_{eb}^2 + 4A_{AF}K_{AF}}}, \tag{1}$$

where, $K_{AF} = M_{AF}H_{a(AF)}/2$ the anisotropy constant of the antiferromagnetic. From (1), the value of H_{eb} is equal 126 Oe. The data fit our results reasonably well.

B. Dynamic properties

For ferromagnetic thin films (free F layer in our case), the FMR frequency can be expressed as

$$f_{FMR} = \frac{\gamma}{2\pi}\sqrt{(H_{a(F)} + H)(H_{a(F)} + H + 4\pi M_F)} \tag{2}$$

where, γ is the gyromagnetic ratio, and H is an external magnetic field directed along an easy axis of the ferromagnetic layer. Notice that when the direction of H is arbitrary the expression for f_{FMR} is more complicated. When introducing the exchange bias field, the magnetic anisotropy field now is a sum of the exchange bias field and the uniaxial anisotropy field. As a result, the FMR frequency for the F/AF bilayer can now be written as follows [13]

$$f_{FMR} = \frac{\gamma}{2\pi}\sqrt{H_{a(F)} + H_{eb} + H}\times \times\sqrt{H_{a(F)} + H_{eb} + H + 4\pi M_F}. \tag{3}$$

Thus, by using different F/AF structures the FMR frequency can be tuned.

Fig. 3. shows the calculated microwave absorption spectra of the free F layer and the F/AF bilayer.

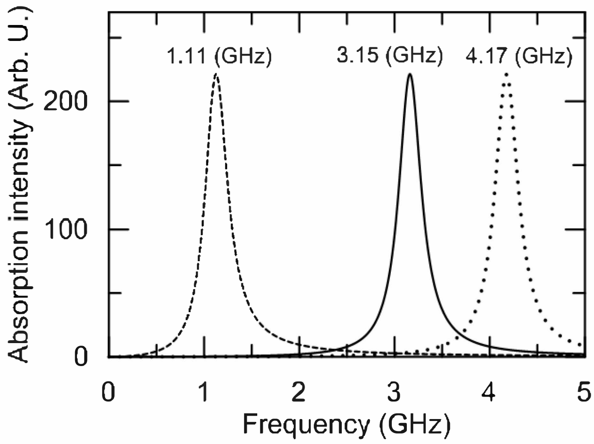

Fig. 3. The microwave absorption spectrum of the free F layer (*solid line*), and spectra of the F/AF structure for two angles between H and the AF easy axis (0° – *dotted line*, 180° – *dashed line*).

The value of applied magnetic field was 100 Oe. One can see that for the case when the angle between the external magnetic field and the AF easy axis is φ = 0° (dotted line on Fig. 3) the FMR frequency of the F/AF structure exceeds f_{FMR} of the free F layer (solid line on Fig. 3) more than 1 GHz. Oppositely, when *H* is reversed and φ = 180° (dashed line in Fig. 3), the FMR frequency of the F/AF bilayer is about three times smaller than the frequency of the free ferromagnetic layer.

Fig. 4. shows the FMR frequency of the F/AF bilayer and the free F layer as a function of angle φ between the external magnetic field and the AF easy axis. As will be seen from the figure, as the angle is increased from 0° to 180° the F/AF resonance frequency is smoothly decreased, whereas the FMR frequency of free F layer has minimum for φ = 90°.

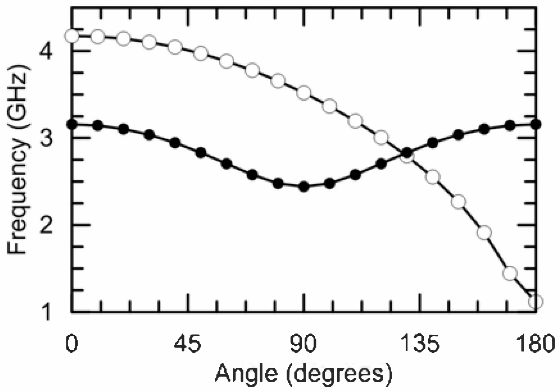

Fig. 4. The FMR frequency of the F/AF bilayer (*open circles*) and the free F layer (*dots*) as a function of angle between the external magnetic field and the AF easy axis.

Notice that when the angle between the external field and the easy axis is 130° the FMR frequency of the F/AF structure is approximately equal to the frequency of the free ferromagnetic layer.

The observed behavior of the F/AF FMR frequency is a result of a unidirectional nature of the anisotropy induced by the exchange interaction between ferromagnetic and antiferromagnetic layers. At the same time, the form of the f_{FMR} (φ) dependence of the free F layer is defined by ordinary uniaxial anisotropy.

IV. Conclusion

In conclusion, in this work we performed the micromagnetic numerical calculations of hysteresis loops and high-frequency absorption spectra of the ferromagnetic antiferromagnetic bilayer. It was shown that depends on the direction of the external magnetic field the FMR frequency of the F/AF structure can be smaller or larger than f_{FMR} of the free F layer. Moreover, for some cases (for the particular angle and value of *H*), when the bias field compensate the external magnetic field and the uniaxial anisotropy $H_{a(F)}$, the FMR frequency can be near to zero. This can find technological applications in future microwave devices.

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